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Laser ranging: To improve economy, performance, and adoption for new applications

Realization of the terrestrial reference frame based on integrated SLR measurements to LEO, geodetic, and Galileo satellites

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INTRODUCTION

Numerous of active low Earth orbiters (LEOs) and Global Navigation Satellite System (GNSS) satellites, including the Galileo constellation, are equipped with laser retroreflectors used for Satellite Laser Ranging (SLR). Moreover, most LEOs are equipped with GNSS receivers for the precise orbit determination. SLR measurements to LEOs, GNSS, and geodetic satellites vary in terms of the registered number of the normal points (NPs) or satellite passes. In 2016-2018, SLR measurements to LEOs constituted 81% of all NPs, whereas 10% of NPs were assigned to GNSS (Fig.1). The remaining 9% of NPs were completed by geodetic satellites, including LAGEOS-1/2. Thus, the question occurs whether those 91% of SLR data can be used for other purposes than just orbit validation.

In this study, we show that the SLR observations to Galileo, passive geodetic and active LEO satellites together with precise GNSS-based orbits of LEOs and Galileo can be used for the determination of SLR station coordinates (Fig.2). Here, we use SLR observations to Galileo, LARES, LAGEOS-1/2, eight LEO satellites (Sentinel-3A, Swarm-A/B/C, Jason-2, Grace-A/B, TerraSAR-X) to investigate whether they can be applied for the reference frame realization and for deriving high-quality station coordinates.

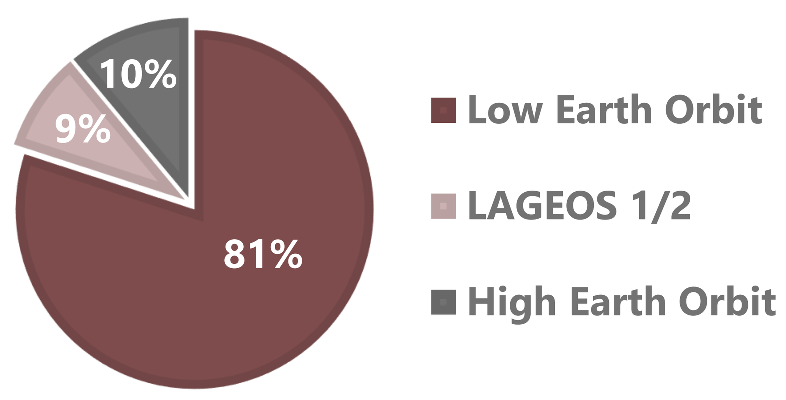

Fig.1. Percentage of SLR observations (normal points) to particular satellite types in 2016-2018

METHODOLOGY AND DATA

First, we combined 1-day normal equations based on SLR range observations, a priori station coordinates from SLRF2014, the 1-day precise GNSS-based orbits of LEOs and Galileo provided by the Astronomical Institute, University of Bern (AIUB), and German Aerospace Center (DLR). The LAGEOS-1/2 and LARES-1/2 orbits were estimated in the calculation process based on SLR data. We used LEO satellite attitude data as a priori, and ERP with near-zero constraints for station coordinates determination. The X, Y pole coordinates, and the UT1-UTC rates were estimated (see Fig.2. and Fig.3.). In our solution we introduced annual mean range biases for each SLR station to particular LEO and Galileo satellites. We generated the 7-day solutions with no-net-rotation (NNR) and no-net-translation (NNT) constraints with estimation of additional parameters. Next, we used the Helmert transformation between obtained coordinates of core stations and the SLRF2014 for the outlier detection (for details see scheme in the Fig. 3.). After the outlier rejection we calculated final solutions with different weighting strategies and excluding some of the satellites from the solutions. Realization of the terrestrial reference frame was calculated using the modified version of the Bernese GNSS software for the 2016.0-2017.0 period.

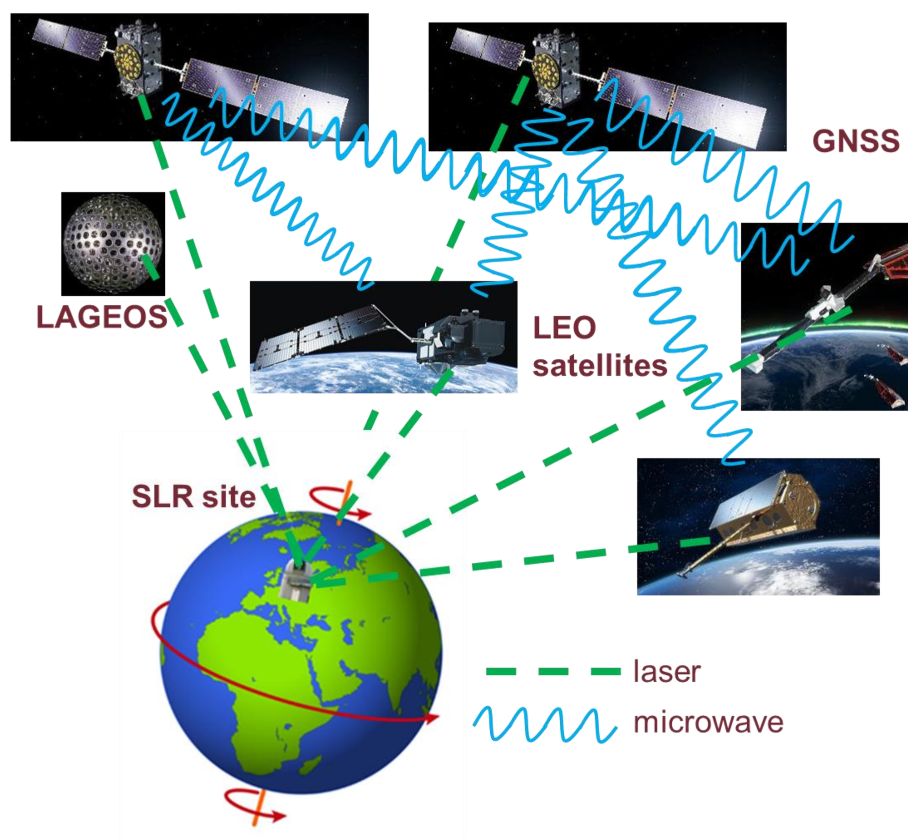

Fig.2. Observation principle in the reference frame realization

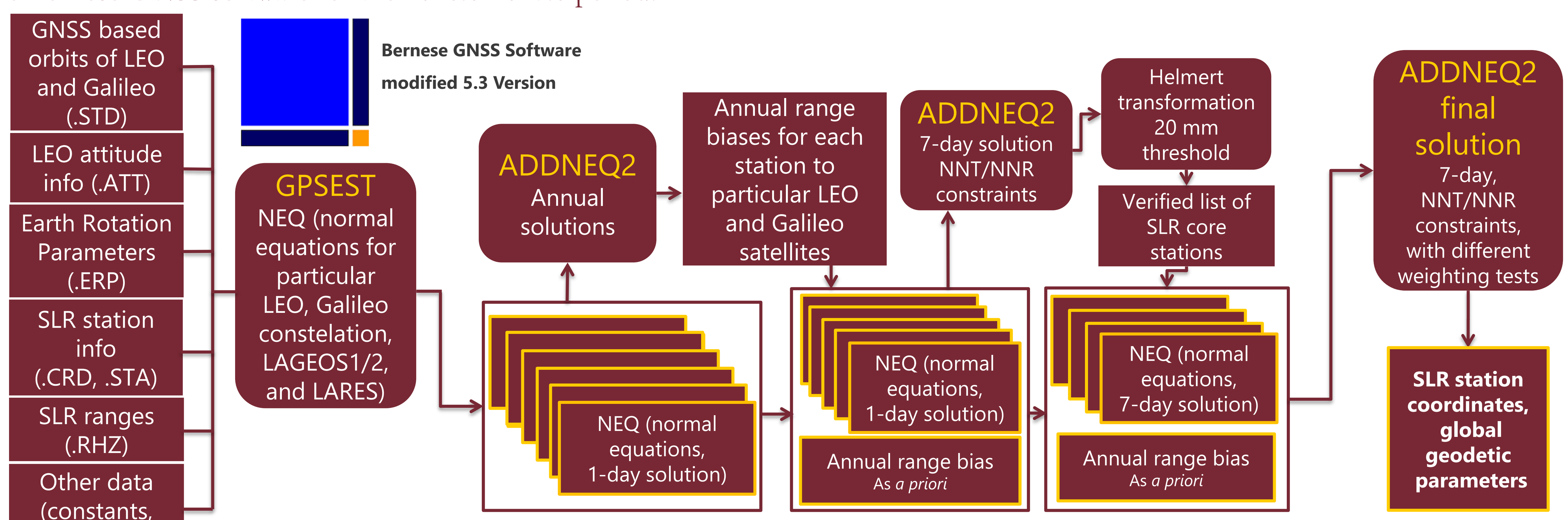

Fig.3. Scheme of the reference frame realization procces

ANNUAL RANGE BIAS CORRECTIONS

In the calculation process it is important to introduce range bias corrections for SLR stations. In our study, we applied annual range biases for each station to particular LEO and Galileo satellites. Mean annual range bias values (Fig. 4.) show that the largest corrections, at the level of -11 to -27 mm, occur for Galileo. In the case of LEOs, the range bias values do not exceed 6 mm and have different signs, depending on the satellite. Fig. 5 shows applied range biases for eight SLR stations to LEOs and Galileo. For Galileo, the largest corrections are applied to the Changchun, Wettzell, and Yarragadee stations (even -50 mm), whereas in the case of LEOs, the highest, negative corrections are applied to the Wettzell and Greenbelt and are at the level of -25 mm and -15 mm respectively. For some of stations (e.g. Changchun, Yarragadee) range biases have positive signs and do not exceed 10 mm.

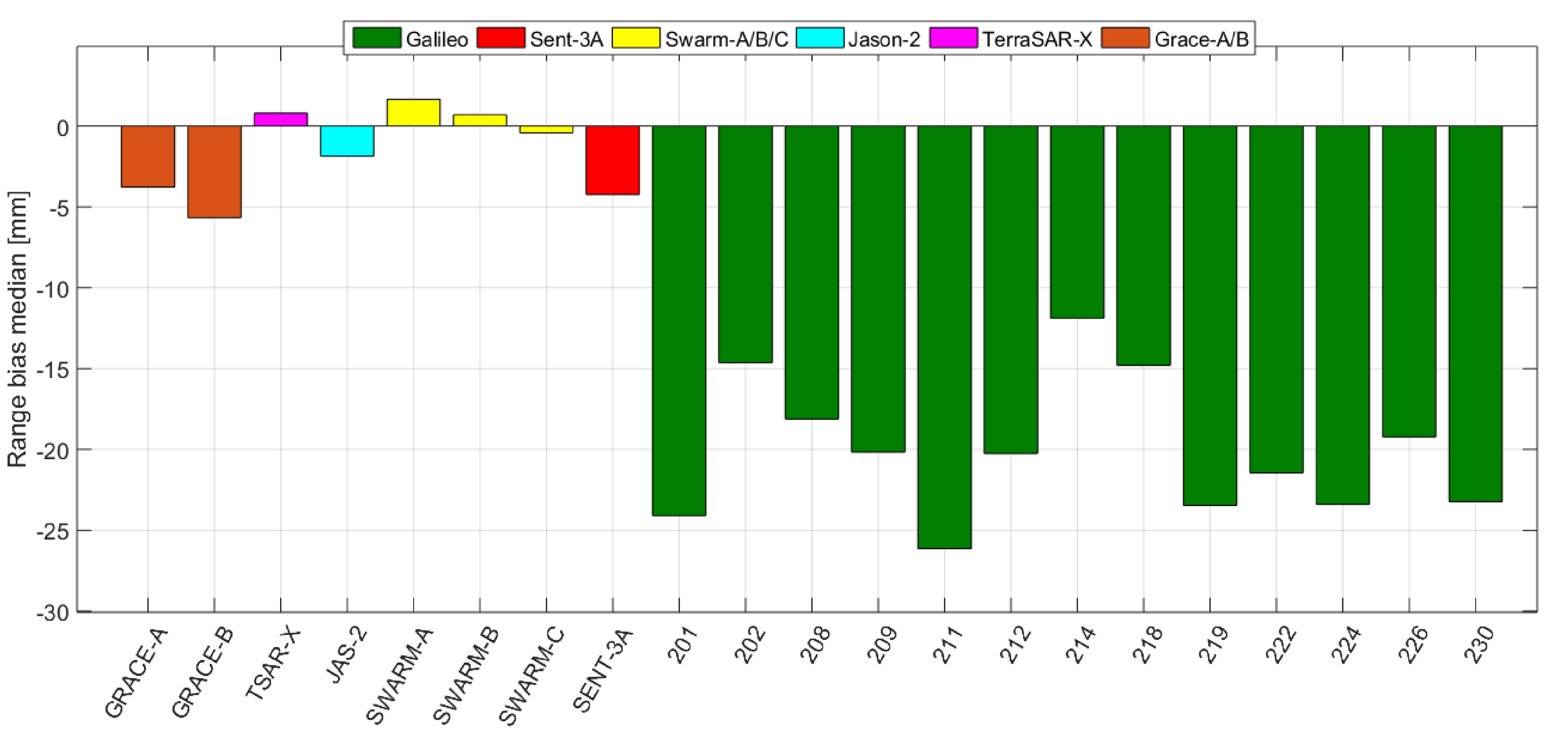

Fig.4. Mean annual (2016) range bias values (calculated for all stations) to particular satellites

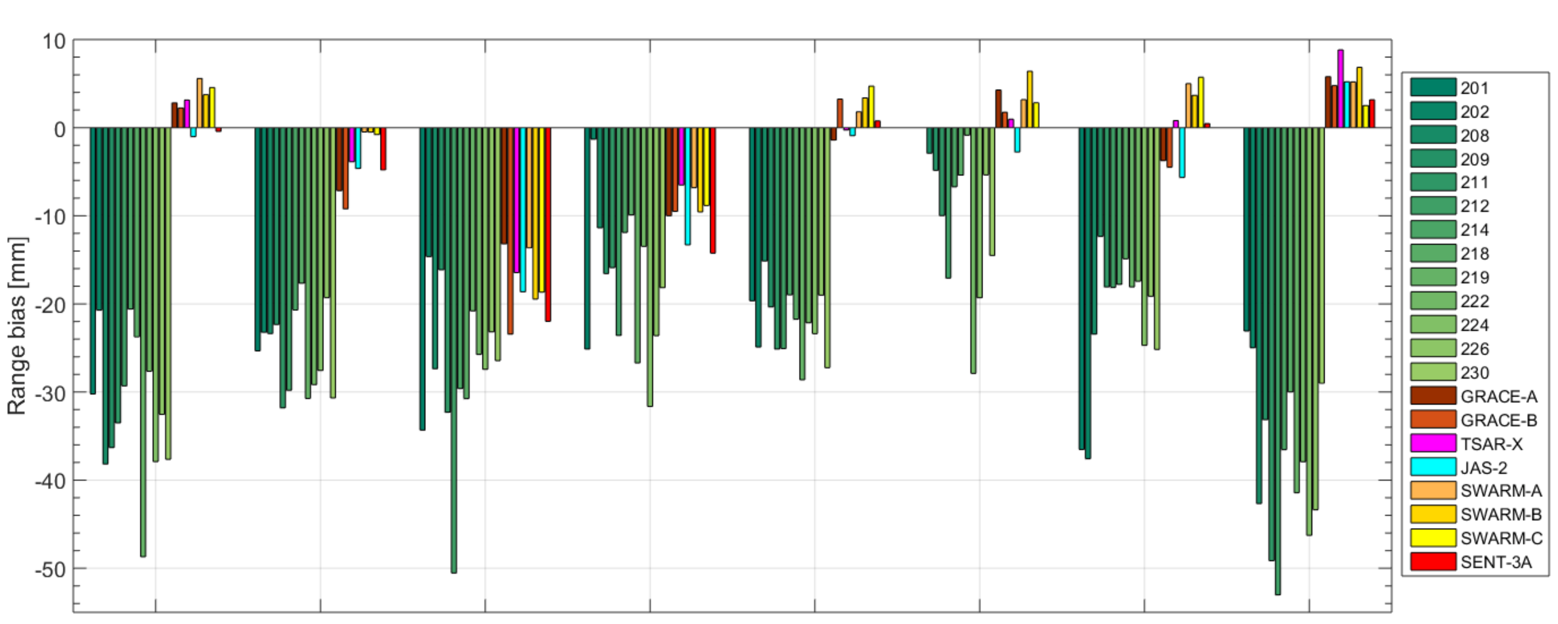

Fig.5. Applied annual range biases (2016) on SLR stations to particular satellites

REFERENCE FRAME REALIZATION & COMBINED SOLUTIONS

For the realization of the reference frame we used different solution scenarios and analyzed SLR station coordinates. We considered results for all stations (37) and core stations (Yarragadee, Greenbelt, Matera, Hartebeesthoek, Haleakala, Zimmerwald, Mt Stromlo, Graz, Herstmonceux, Potsdam) by means of interquartile ranges (IQR), w.r.t SLRF2014.

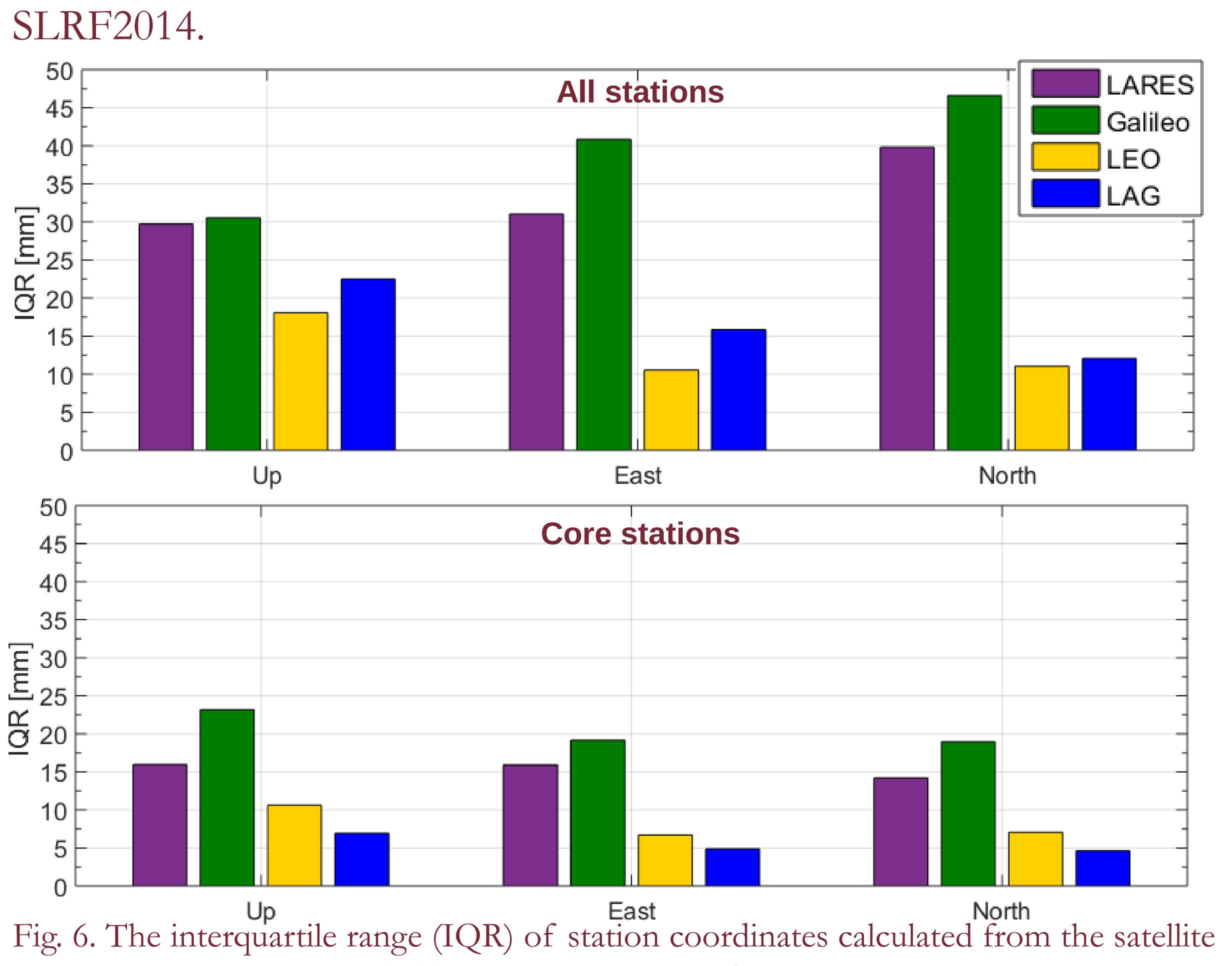

Fig. 6. The interquartile range (IQR) of station coordinates calculated from the satellite type only solutions w.r.t SLRF2014 (top-all stations, bottom-core stations)

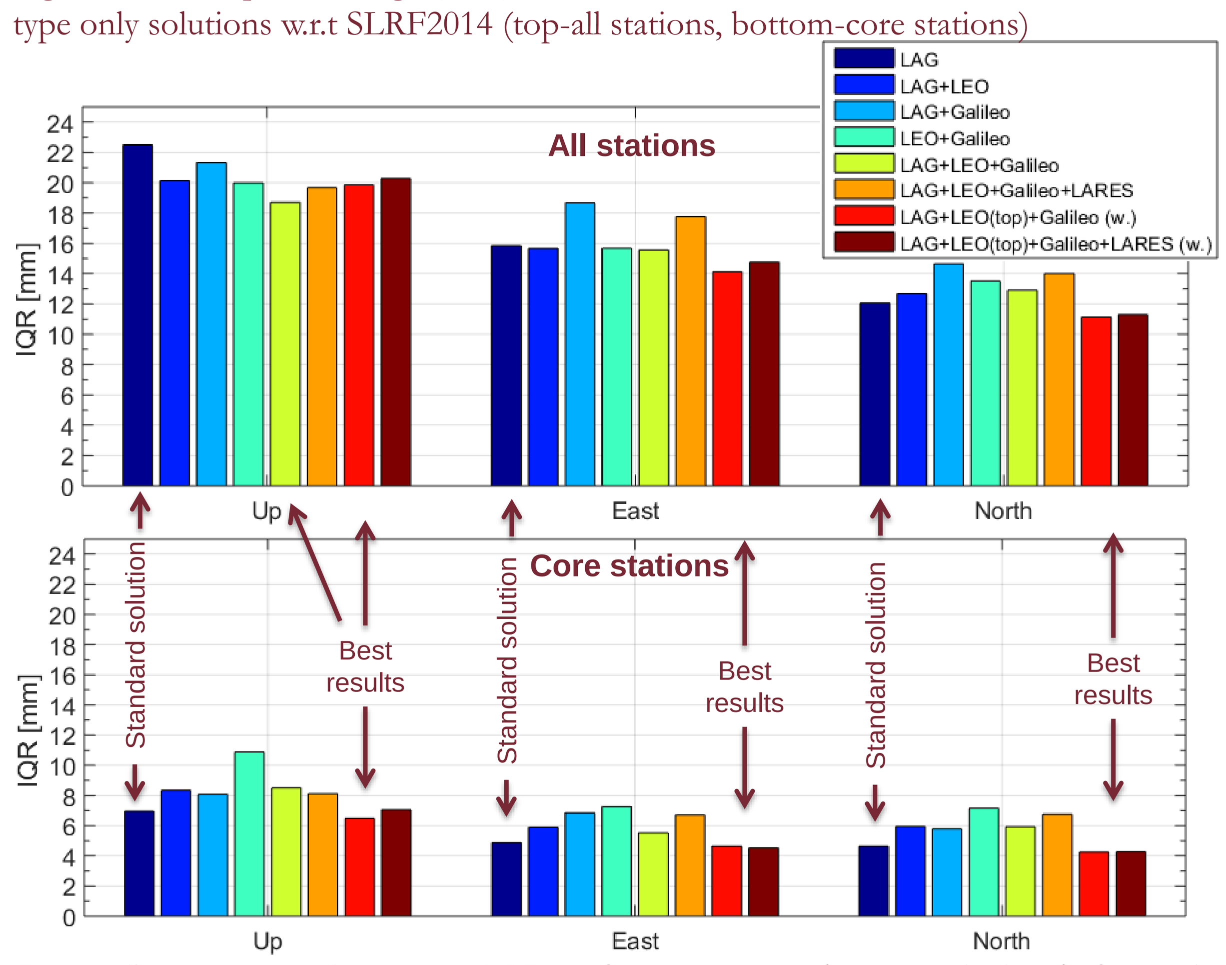

Fig.7. The interquartile range (IQR) of station coordinates calculated from the combined solutions w.r.t SLRF2014 (top-all stations, bottom-core stations, w.- weighted solutions, top- top performing LEOs, i.e., Sentinel-3A, Swarm-A/B/C, Jason-2)

First, we calculated solutions based on LARES-only, Galileo-only, LAGEOS-only (standard solution) and LEOs-only data (Fig. 6). LEO-only solutions is 5 mm better than the standard LAGEOS solutions for all stations (Fig. 6 top) and yet they are worse by 2-4 mm in the case of core sites (Fig 6 bottom). LARES-only and Galileo-only solutions are insufficient for all components with IQR above 30 mm for all stations and above 15 mm for core station.

Eventually, we tested different combinations of data solutions, considering the satellite type, reducing the number of LEO satellites or weighting of observations (Fig.7). In the case of all stations (Fig. 7, top) the IQR values for the Up component are over 2-3 mm better (w.r.t standard LAGEOS) for all combinations (especially for LAG+LEO+Galileo). In the case of the horizontal components the best results, with 1-2 mm improvement, occur for combinations of LAG+LEO(top performing)+Galileo and LAG+LEO(top performing)+Galileo+LARES, both with weighting of observations (variance scaling factors for data type are: 1 for LAG, 0.25 for LEO, 0.25 for Galileo and 0.11 for LARES). In the case of core sites (Fig. 7 bottom) the best results are also for combinations of LAG+LEO(top performing)+Galileo and LAG+LEO(top performing)+Galileo + LARES, both with weighting of observations. In the weighted combined solutions, the IQR values for the Up component are similar to that from LAGEOS-only, at the level of 7 mm, whereas the horizontal components are slightly better, at the level of 5 mm.

CONCLUSIONS

- SLR stations have been providing observations to a large number of new LEO and Galileo satellites
- Each SLR site requires different bias correction individually for a particular satellite
- SLR observations to Galileo+LEO+LAGEOS+LARES with proper weighting of observations allow for the determination of station coordinates with the accuracy of 4-8 mm (core sites)
- Combination of SLR data to different satellite types can be applied for the reference frame realization

In 2016 Galileo did not have a full operational status. Further improvement may be expected!

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